Single-top-squark production via R-parity-violating supersymmetric couplings in hadron collisions

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Single-top-squark production via $qq' \to \bar{\tilde{t}}_1$ probes R-parity-violating extensions of the minimal supersymmetric standard model though the λ''_{3ij} couplings. For masses in the range 180–325 GeV, and $\lambda''_{3ij} > 0.02$–0.06, we show that discovery of the top squark is possible with 2 fb^{-1} of integrated luminosity at run II of the Fermilab Tevatron. The bound on λ''_{3ij} can be reduced by up to an order of magnitude with existing data from run I, and by two orders of magnitude at run II if the top squark is not found.

In supersymmetric extensions of the standard model, particles may be assigned a new quantum number called R-parity (R_p) [1]. The particles of the standard model are R_p even, and their corresponding superpartners are R_p odd. The bounds on possible R_p-violating couplings are relatively restrictive for the first two generations of quarks and leptons, but much less so for states of the third generation [2]. If R_p is conserved, as is often assumed, superpartners must be produced in pairs, each of which decays to a final state that includes at least one stable lightest supersymmetric particle (LSP). The production rates for pairs of strongly interacting supersymmetric particles, the squarks and gluinos, benefit from the large color couplings of these superpartners to the incident light quarks and gluons in hadronic scattering subprocesses. However, in many models, the squarks and gluinos are relatively heavy, and therefore their pair production incurs a large phase space suppression.

In this Letter, the s-channel production of a *single* squark through an R_p-violating mechanism [3] is considered. The motivation is that the greater phase space offsets the reduced coupling strength in the production. The focus is on the relatively light top squark $\tilde{t}_1$ and its subsequent R_p-*conserving* decays. Thus, the R-parity violation penalty is paid only once, in the initial production, and is offset by the greater phase space relative to pair production.

Beginning with the superpotential for R_p-violating couplings, we write the partonic cross section for the process $qq' \to \bar{\tilde{t}}_1$ and compare with that for pair production. Then discussing observability, we focus on one clean R_p-conserving decay, $\tilde{t}_1 \to b\tilde{\chi}_1^+$, with $\tilde{\chi}_1^+ \to l^+ + \nu + \tilde{\chi}_1^0$. Here, l is an electron or muon, and the $\tilde{\chi}_1^+$ and $\tilde{\chi}_1^0$ are the chargino and lowest-mass neutralino states of the minimal supersymmetric standard model (MSSM). For top-squark masses in the range of 180–325 GeV, we sim-

ulate both the signal and standard model background processes and thereby show that the top squark can be discovered, or the current bound on the size of the R_p-violating couplings λ''_{3ij} can be reduced by up to one order of magnitude with existing data and by two orders of magnitude at the forthcoming run II of the Fermilab Tevatron.

In general it is possible to have R_p-violating contributions to the MSSM superpotential of the baryon- or lepton-number violating type. However, limits on the proton decay rate severely restrict their simultaneous presence. We therefore assume the existence of a baryon-number-violating coupling only of the form [4]

$$\mathcal{W}_{\slashed{R}_p} = \lambda''_{ijk} U_i^c D_j^c D_k^c .\tag{1}$$

Here, U_i^c and D_i^c are right-handed-quark singlet chiral superfields, i, j, k are generation indices, and c denotes charge conjugation.

In four-component Dirac notation, the Lagrangian that follows from this superpotential term is

$$\mathcal{L}_{\lambda''} = -2\epsilon^{\alpha\beta\gamma}\lambda''_{ijk}\left[\widetilde{u}_{Ri\alpha}\overline{d_{j\beta}^c}P_R d_{k\gamma} + \widetilde{d}_{Rj\beta}\overline{u_{i\alpha}^c}P_R d_{k\gamma}\right.$$
$$\left. + \widetilde{d}_{Rk\gamma}\overline{u_{i\alpha}^c}P_R d_{j\beta}\right] + h.c. ,\tag{2}$$

where $j < k$. For production of a right-handed top squark via an s-channel diagram $\bar{d}^j \bar{d}^k \to \widetilde{u}_R^i$ the relevant couplings are λ''_{312}, λ''_{313}, and λ''_{323}. The most direct limits on these couplings come from the measurement of R_l, the partial decay width to hadrons over the partial decay width to leptons of the Z boson. For the top-squark masses considered, R_l provides 95% confidence-level upper bounds of $\lambda''_{3ij} < 1$ [2].

The color- and spin-averaged partonic cross section for inclusive $\tilde{t}_1$ production is

$$\hat{\sigma} = \frac{2\pi}{3}|\lambda''_{3ij}|^2\frac{\sin^2\theta_{\widetilde{t}}}{m_{\tilde{t}_1}^2}\delta(1 - m_{\tilde{t}_1}^2/\hat{s}) ,\tag{3}$$

where $\sqrt{\hat{s}}$ is the partonic center of mass energy, and $\theta_{\widetilde{t}}$ relates the right- and left-handed top-squark interaction states to the mass eigenstates. The hadronic cross section depends on the following combinations of incident parton distribution functions (PDF's): $d \otimes s$, $d \otimes b$, and $s \otimes b$, where d, s, and b denote the PDF's of the down, strange, and bottom quarks, respectively.

The mass dependences of the cross sections for single and pair [5] production of top squarks differ significantly, as shown in Fig. 1. The curves are based on CTEQ4L PDF's [6] and $\lambda''_{3ij} = 0.1$. Even if λ''_{3ij} is reduced to 0.01, two orders of magnitude below the current bound, the single-top-squark rate exceeds the pair rate for all $m_{\widetilde{t}_1} > 100$ GeV. The parton luminosities determine that the contribution to the total cross section of the terms proportional to $\lambda''_{312} : \lambda''_{313} : \lambda''_{323}$ is about 0.75 : 0.20 : 0.05 at $m_{\widetilde{t}_1} = 200$ GeV. For simplicity, we define $\lambda'' \equiv \lambda''_{312} = \lambda''_{313} = \lambda''_{323}$. Our numerical results represent the sum of $\widetilde{t}_1$ and $\bar{\widetilde{t}}_1$ production.
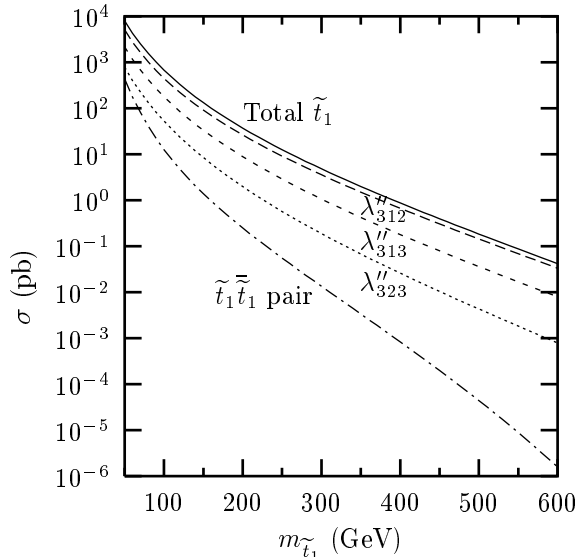

FIG. 1. Cross section for R-parity-violating production of a single top squark at run II of the Fermilab Tevatron ($\sqrt{S} = 2$ TeV) with $\lambda''_{3ij} = 0.1$ compared with the R-parity-conserving production cross section for top-squark pairs versus $m_{\widetilde{t}_1}$.

An evaluation of the possibility for detection of a single top squark requires discussion of the likely decay modes of the squark and an estimation of standard model backgrounds. In the R_p-conserving MSSM, the up-type squark $\widetilde{u}^k$ can decay into charginos and neutralinos via the two-body processes $\widetilde{u}^k \to d^k + \widetilde{\chi}^+_j$ ($j = 1, 2$) and $\widetilde{u}^k \to u^k + \widetilde{\chi}^0_j$ ($j = 1, 2, 3, 4$), where $\widetilde{\chi}^+_j$ and $\widetilde{\chi}^0_j$ represent a chargino and neutralino, respectively. Various three body modes are possible, including $\widetilde{t}_1 \to W^+ + b + \widetilde{\chi}^0_1$, which is similar to decay into the top quark (followed by top decay to $W^+ + b$) but softer; and $\widetilde{t}_1 \to c + \widetilde{\chi}^0_j$ via a flavor-changing loop process.

In the R_p-violating MSSM, the right-handed up-type squark $\widetilde{u}^k_R$ can also decay into quark pairs $\widetilde{u}^k_R \to \bar{d}^j + \bar{d}^i$ via the λ'' couplings. The branching fraction into two jets is shown in Fig. 2. If λ'' is large, the decay to quark jets dominates. However, as shown below, the R_p-conserving decay still produces a measurable and useful cross section.
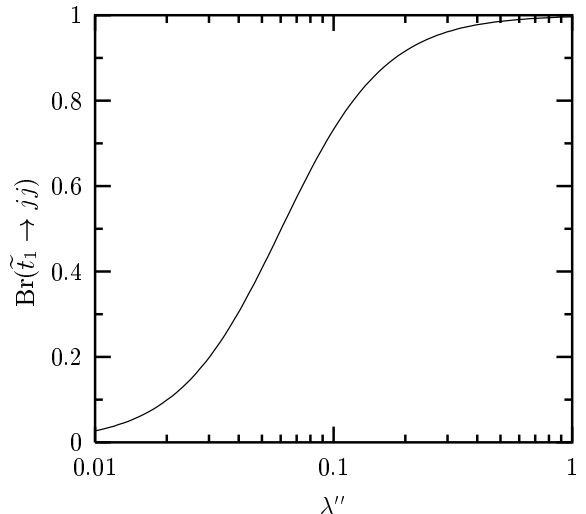

FIG. 2. Branching ratio for the top squark to decay into two jets via the R-parity-violating coupling λ'' as a function of the coupling.

For the remainder of this Letter, we focus on the two-body decay mode [7] $\widetilde{t}_1 \to b + \widetilde{\chi}^+_1$, with $\widetilde{\chi}^+ \to l + \nu + \widetilde{\chi}^0_1$. Here, l denotes an electron or muon, which usually comes from a W. When R-parity is violated, $\widetilde{\chi}^0_1$ is no longer stable; however, its lifetime is long ($c\tau > 100$ m, cf. the first paper of Ref. [2]), and thus we expect it to decay outside of the detector.

To obtain the relevant masses and decay branching fractions, we adopt a minimal supergravity model [8]. We begin with common scalar and fermion masses of $m_0 = 100$ GeV and $m_{1/2} = 150$ GeV, respectively, at the Grand Unified Theory (GUT) scale. We choose a trilinear coupling $A_0 = -300$ GeV and the ratio of the Higgs vacuum expectation values $\tan \beta = 4$. The absolute value of the Higgs mass parameter μ is fixed by electroweak symmetry breaking and is assumed positive. Superpartner masses and decay widths are calculated with ISAJET [9]. At the weak scale, $m_{\widetilde{t}} = 183$ GeV, $m_{\widetilde{\chi}^0_1} = 55$ GeV, $m_{\widetilde{\chi}^\pm_1} = 103$ GeV, and $\sin \theta_{\widetilde{t}} = 0.8$. In order to isolate the effects of the R_p-violating sector, we vary m_0 and keep the other supersymmetric parameters fixed. Since the gaugino masses depend primarily on the choice of $m_{1/2}$, variation of m_0 allows us to vary $m_{\widetilde{t}_1}$ without any appreciable change in the masses of the decay products, or the mixing angle $\theta_{\widetilde{t}}$.

The signal of interest consists of a tagged b-quark jet, a lepton, and missing transverse energy associated with the unobserved neutrino and $\widetilde{\chi}^0_1$. The dominant backgrounds, in order of importance, arise from production and decay of the standard model processes Wc, with a charm quark c that is mistaken for a b; Wj, with a hadronic jet that mimics a b; $Wb\bar{b}$; $Wc\bar{c}$; and single-top-quark production via Wg fusion. For these background processes, we work with tree-level matrix elements obtained from MADGRAPH [10] convolved with leading-

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order CTEQ4L [6] parton distribution functions, at a hard scattering scale $\mu^2 = \hat{s}$. In an experimental analysis, the Wj background will be normalized by the data. To simulate the resolution of the hadron calorimeter, we smear the jet energies with a Gaussian whose width is $\Delta E_j/E_j = 0.80/\sqrt{E_j} \oplus 0.05$ (added in quadrature).

We simulate the acceptance of the detector by using the selections listed in Table I. The assumed coverage in rapidity for taggable b-quark jets and leptons is smaller for run I than for run II. However, the signal and background are similar in shape in these variables, and thus S/B is not sensitive to this cut. The lepton must be isolated from any jets, as defined by a cone of radius ΔR, or it is considered missed. Similarly, an isolation cut is used for the b-quark jet in order to help identify it. We assume a b-tagging efficiency of 60% (50% for run I) with a mistag rate of 15% for charm quarks and 0.5% for light quarks [11].

As expected from the primary decay, $\tilde{t}_1 \to b + \tilde{\chi}_1^+$, the distribution in the transverse energy E_T of the b quark is peaked sharply near the maximum value allowed kinematically. The spectrum of the background b quark is soft, and thus we impose a hard cut ($E_{Tb} > 40$ GeV) on the minimum E_T of the b-quark jet. The b-jet becomes too soft to be detected if $m_{\tilde{t}_1} \leq m_{\tilde{\chi}_1} + E_T^{\text{cut}}$. This contributes to a lower limit on $m_{\tilde{t}_1}$ below which our proposed search mode is not useful.

The background from single-top-*quark* production will produce a peak in any mass reconstruction. We utilize the fact that single top quarks are often produced with extra hard jets, and impose a "jet veto". We require that there be no hard jets ($E_{Tj} > 20$ GeV, $|\eta| < 2.5$), beyond the one that is b-tagged, in the hadron calorimeter. After the jet veto, the remaining background is due almost entirely to misidentified charm and light-quark jets from Wc and Wj production. The transverse energy of the lepton tends to be relatively soft for the signal at lower $m_{\tilde{t}_1}$, whereas it peaks around 45 GeV when it comes from the W in the background. A cut to remove hard leptons, with $E_{Tl} > 45$ GeV, reduces the background by a factor of 2 with little effect on the signal at low masses. The final significance for the signal at run II is barely changed by this "lepton veto", but it is especially helpful for the run I data.

TABLE I. Cuts used to simulate the acceptance of the detector at the Tevatron run II, and run I (in parentheses if different). The lepton veto ($E_{Tl} < 45$ GeV) is optimized for small top-squark mass.

$|\eta_b| < 2$ (1)	$E_{Tb} > 40$ GeV
$|\eta_l| < 2.5$ (1.1)	$E_{Tl} > 15$ GeV (20 GeV)
$|\eta_j| < 2.5$	$E_{Tj} > 20$ GeV
$|\Delta R_{bj}| > 0.7$	$|\Delta R_{jl}| > 0.7$
$\not{E}_T > 20$ GeV	$E_{Tl} < 45$ GeV

Shown in Fig. 3 is an example of the signal and background. For this case, $m_{\tilde{t}_1} = 242$ GeV and $\lambda'' = 0.03$. The mass variable is defined as $M^2 = (P_b + P_l + P_X)^2$ where the P_b and P_l are the four-momenta of the b and lepton. The four-momentum P_X is defined such that its three-momentum balances that of the b and lepton, and $P_X^2 \equiv 0$. The reconstructed Wj background turns on at $m_W + E_{Tb}^{\text{cut}}$, and thus peaks at 150 GeV, before falling rapidly with mass. The signal in Fig. 3 would constitute a discovery at the level of 5σ with an integrated luminosity of 2 fb^{-1} at $\sqrt{S} = 2$ TeV. The significance is calculated for a mass window of ± 30 GeV about the center of the peak. A change of the window size to either ± 20 GeV or ± 40 GeV produces the same significance to within a few percent. When $m_{\tilde{t}_1}$ is reduced to 183 GeV, the signal and background spectra peak at about the same location, and sensitivity to the signal begins to be lost.
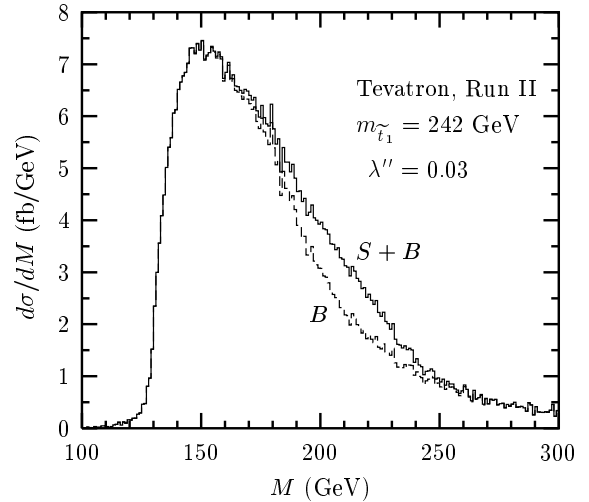

FIG. 3. The reconstructed-mass M distribution for single-top-squark production (S) and backgrounds (B) at the Tevatron ($\sqrt{S} = 2$ TeV) for a top-squark mass $m_{\tilde{t}_1} = 242$ GeV. The coupling $\lambda'' = 0.03$ produces the minimum signal for a 5σ significance at this mass.

Examination of the structure of the cross section involving R_p-*conserving* decay modes reveals that as λ'' grows, the decrease in branching fraction is compensated by the increase in cross section. As depicted in Fig. 4,

$$\sigma \propto \frac{|\lambda''|^2}{|\lambda''|^2 + f(R_p)} , \qquad (4)$$

where $f(R_P)$ is a constant times the branching fraction into R_p-conserving modes. As $\lambda'' \to \infty$, the cross section goes to a constant; whereas, when $\lambda'' \to 0$ the cross section decreases as $|\lambda''|^2$. The relationship $S/\sqrt{B} \propto |\lambda''|^2/\sqrt{B}$, valid for small λ'', implies a lower limit on the values of λ'' that can be probed. On the other hand, this relationship highlights an insensitivity to variations in the estimate of the background.
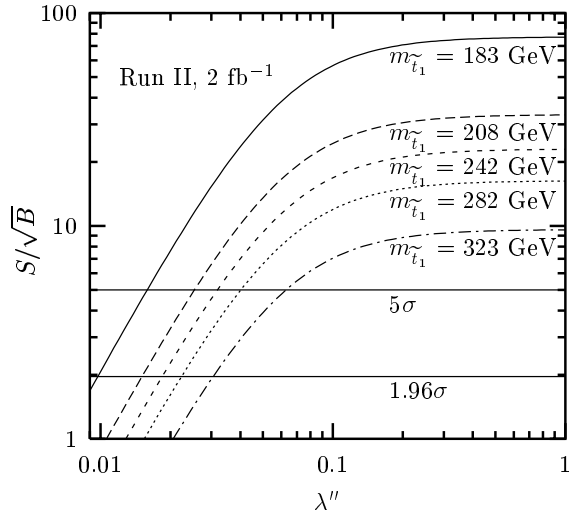
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FIG. 4. Statistical significance of the single-top-squark signal ($S/\sqrt{B}$) in run II of the Tevatron ($\sqrt{S} = 2$ TeV, 2 fb^{-1}) versus λ'' for a variety of top-squark masses.

In Fig. 5, we show the reach in λ'' for $180 < m_{\widetilde{t}_1} < 325$ GeV. With an integrated luminosity of 2 fb^{-1} at $\sqrt{S} = 2$ TeV, discovery at the level of 5σ is possible provided that $\lambda'' > 0.02$–0.06. Otherwise, a 95% confidence-level exclusion can be set for $\lambda'' > 0.01$–0.03. For the lower integrated luminosity and energy of the existing run I data, values of $\lambda'' > 0.03$–0.2 can be excluded at the 95% confidence level if $m_{\widetilde{t}_1} = 180$–$280$ GeV. In the limit that only one of the λ''_{3ij} couplings is non-zero, a conservative estimate of the sensitivity may be obtained by dividing by the relative contribution of the coupling to the production cross section presented earlier.
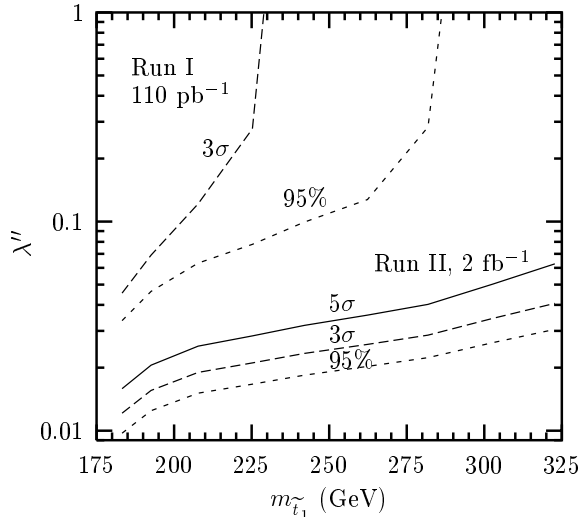

FIG. 5. Lower limits on discovery ($S/\sqrt{B} = 5$), evidence ($S/\sqrt{B} = 3$), and 95% confidence-level exclusion ($S/\sqrt{B} = 1.96$) for λ'' versus top-squark mass in run I of the Tevatron ($\sqrt{S} = 1.8$ TeV, 110 pb^{-1}), and in run II ($\sqrt{S} = 2$ TeV, 2 fb^{-1}).

We conclude that, as long as the R_p-conserving decay $\widetilde{t}_1 \rightarrow b\widetilde{\chi}_1^+ \rightarrow l\nu\widetilde{\chi}_1^0$ is allowed, it should be possible to discover the top squark at run II of the Fermilab Tevatron, for $180 < m_{\widetilde{t}_1} < 325$ GeV and $\lambda''_{3ij} > 0.02$–0.06, or to lower the direct limit on λ'' by two orders of magnitude. Existing data from run I of the Tevatron should allow a reduction of the limit on λ'' by an order of magnitude. With such a reduction, one can establish that R_p-violating decay is unlikely and rule out most of the possible influence of the top squark on single-top-quark production and decay. These points and details of our calculation will be presented elsewhere.

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